Innovative Confinement Concepts

Issues and Challenges

OFES Budget Planning Meeting
For FY2007

March 15, 2005

Glen A. Wurden

NNSA Los Alamos

Innovative Confinement Concepts (Concept Exploration Level)

- Leading-edge plasma science across the nation.
- Small-scale experiments as the premier, cost-effective method to train the next generation of plasma researchers (more than 100 students/year)
- Outstanding venues to test ideas for implementation on mid and large scale fusion devices.
- The US program leads the world in confinement innovation.

U.S. Fusion Program Participants

ANL	Argonne National Laboratory
INL	Idaho National Laboratory
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
PPPL	Princeton Plasma Physics Laboratory
SNL	Sandia National Laboratories
SRNL	Savannah River National Laboratory

● NATIONAL LABORATORY ● UNIVERSITY ● INDUSTRY ● INTER-GOVT AGENCY

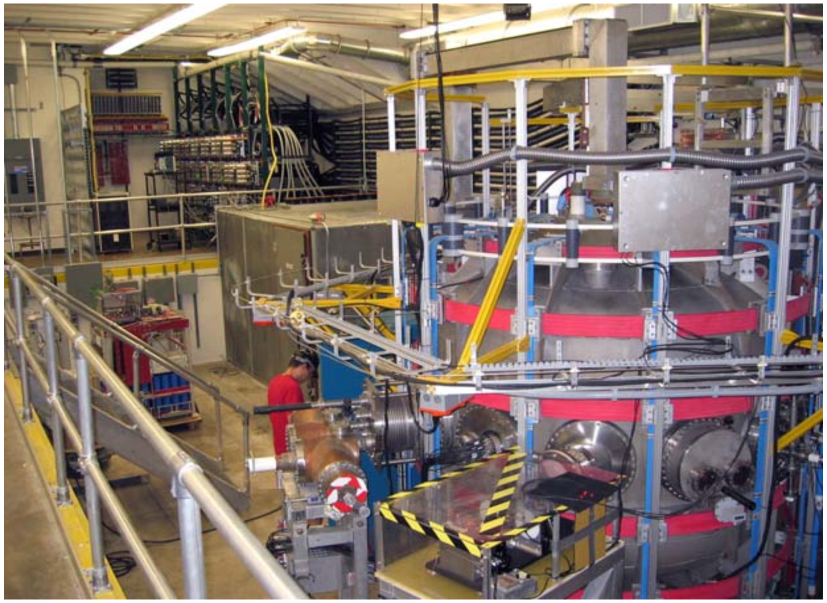
MARCH 8, 2005

ICC – CE Program supports many concepts ($20.8M)

“Strong External B field”		“Advanced Toroidal and Other”		
Tokamak innovations & physics	**Stellarator**	**Self-organized**	**high-pressure and high-B**	**Other**
HBT-EP Resistive-wall stab. Tokamak trans. phys. Divertor innovation Pegasus HIT-II LTX	HSX CTH QPS	Spheromak (SSPX, HIT-SI, CalTech) FRC (TCS-rotomak, Odd-parity RMF, SSX, Theory & Misc.)	Magneto-Inertial Fusion (FRX-L, Solid liner, theory, stand-off driver) Inverse Z-pinch Accelerated FRC Flow Pinch (ZAP) CT Accel Plasma jets	LDX Mary. Centr. Exp. Magneto-Bern. Exp. Inert. Elect. Conf. ICC Center
$3.9M	**$3.4M**	**$6 M**	**$4M**	**$3.5M**

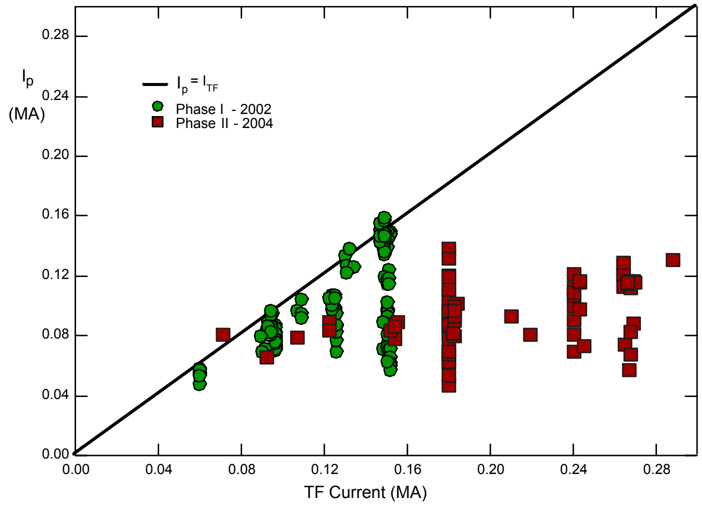
PEGASUS: Explore plasma limits as $A \rightarrow 1$

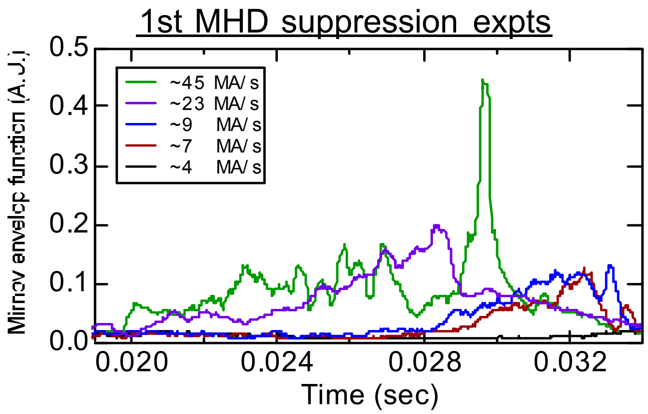
- Stability and confinement at high I_p/I_{TF}: Limits on β_t and $I_N \sim 6I_p/I_{TF}$ (kink) as $A \rightarrow 1$
  - Low field, OH and HHFW $\rightarrow$ high I_N & β_t



- Recent Accomplishments:
  - Almost all-new laboratory facility built
    - Programmable & controllable coil currents
    - New low-L TF system
  - First plasma with new facility
    - Low-power OH
    - Extend TF operating range
    - Recovered earlier low-A, low-l_i regime

- Present campaign:
  - New high-power OH system deployed
  - Employ new control tools to suppress MHD
  - Extend operating space to move to $I_p/I_{TF} > 1$





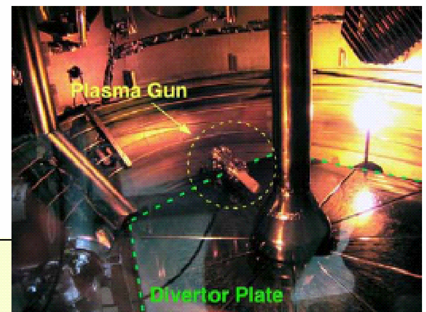
PEGASUS FY07: High I_N, Noninductive ST Formation, Heating, CD

- **FY07: a 3-pronged campaign proposed**

1) Use new tools to explore low-A, high I_N, high β_t regime

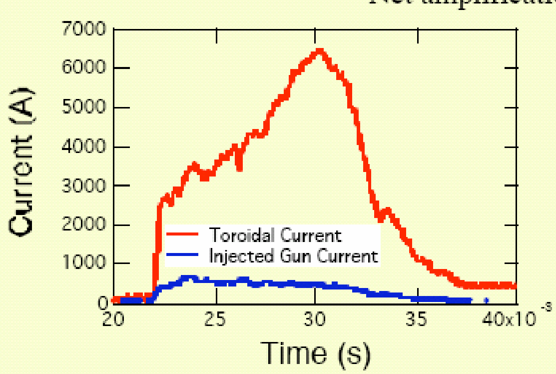
2) High-power ST EBW tests at 2.45 GHz (w/PPPL)

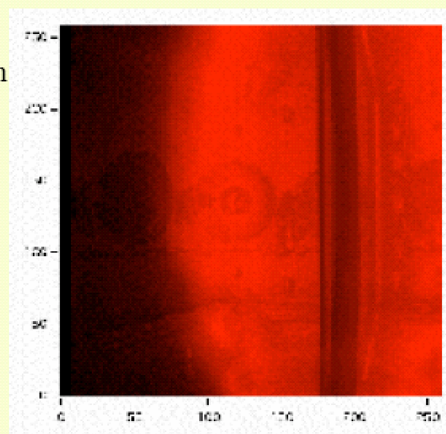
3) Extend non-inductive startup with local plasma current gun array

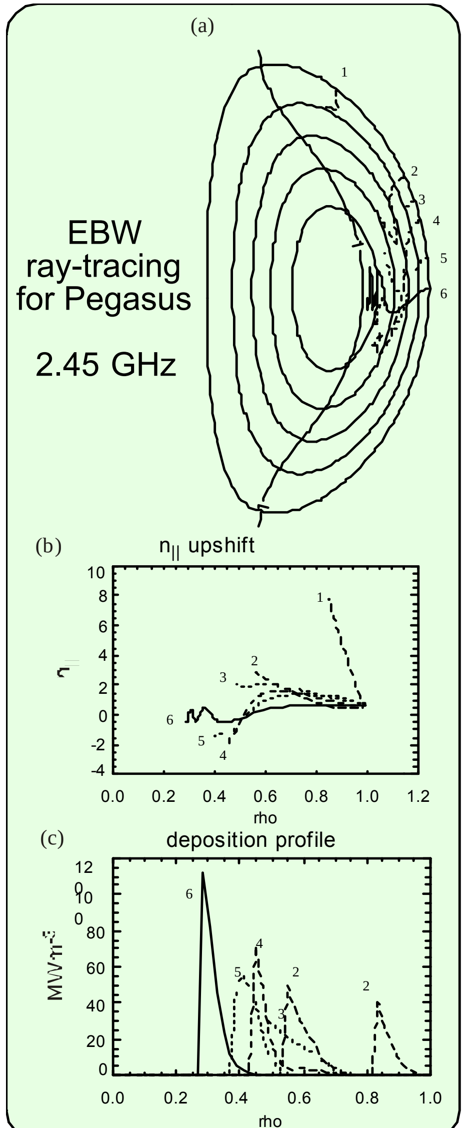


SN 24438 Vbias = 400 V
Single gun in lower divertor region:

High current => Filaments Merge
Net amplification







Results from the CDX-U/LTX lithium program

CDX-U LTX

- The Lithium Tokamak program on CDX-U and LTX is designed to investigate very low recycling regimes. Offers a *fundamental change* in magnetic confinement:
  - Elimination of electron conduction losses, control of the density and temperature profiles through fueling, improved stability.
- CDX-U experiments with a 2000 cm^2 liquid lithium filled limiter complete. **Results:**
  - Recycling is greatly reduced.
    - » Factor-of-eight increase in gas puffing is required to maintain density.
    - » Plasma density pumps out in ~ 1 τ_E without strong gas puffing.
  - Record low loop voltages for ohmically driven small tokamaks.
    - » Resistive loop voltage at constant plasma current only 0.3 - 0.5V.
      - ***6 - 10*** $\times$ reduction in V_{loop} compared to nonlithium operation.
      - Comparable to ***TFTR*** ohmic loop voltage.
  - 10 × reduction in oxygen radiation.
  - 2.5 × increase in ion temperature.
  - 50% increase in edge electron temperature.
  - Broader current profiles. 2 × reduction in internal inductance.
  - *No ejection of lithium*, due to design of the limiter (lithium surface, currents || **B**).
- Progress towards LTX:
  - Lithium coating systems undergoing first tests.
  - Conformal shell (main LTX component) is in fabrication.

PPPL PRINCETON PLASMA PHYSICS LABORATORY

LTX budget and schedule (FY07)

CDX-U

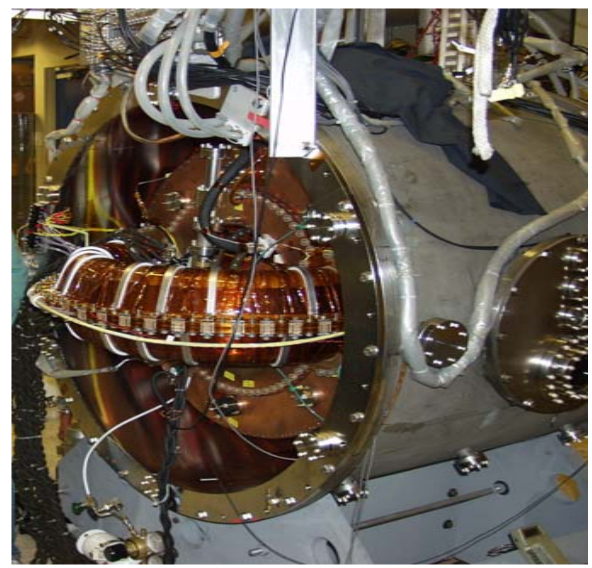
- Baseline FY07 budget: $1,035k (FY05 number).
- FY07 tasks:
  - Final assembly of LTX
    - Modified (recased & jointed) toroidal field coils
    - External poloidal field coils
  - Reinstallation of the CDX-U diagnostic set
  - First plasma in mid-FY07
  - Lithium wall operation in late FY07
- Current budget is 20% below original (reduced) funding profile (Dec. 03)
  - Delay plasma operations until FY07
  - ORNL pellet injector not funded
  - Thomson scattering not available, many other diagnostic impacts
- For optimal use, a 220k incremental in FY07 would fund Thomson scattering
- Impact of additional 10% reduction:
  - Partial implementation of OH system - single swing only
  - Reduce coverage of lithium coating systems - fewer coaters

Recent results from the HIT program

- The goal of the HIT program is to develop helicity injection current drive, which has the potential of being a very efficient steady state current drive. Presently, we are studying steady inductive helicity injection on a high-beta spheromak.
- Recent achievements with CHI on the ST HIT-II
  - Achieved 100 kA of closed flux current with transient CHI. This is a solenoid free startup with no time variations in the flux boundary conditions.
  - Discovered criteria for poloidal flux amplification and the possibility of closed flux sustainment with steady state CHI.

$$I_{TF} < 27 I_{inj}$$

  - Achieved 350 kA in this regime
  - Demonstrated edge profile control
  - Application of CHI on NSTX
- With Steady Inductive Helicity Injection (SIHI)
  - Installed HIT-SI on HIT facility $\Rightarrow$
    - Interferometry
    - Spectroscopy
    - More power (5 MW achieved)



HIT-SI experiment

HIT plans for FY07

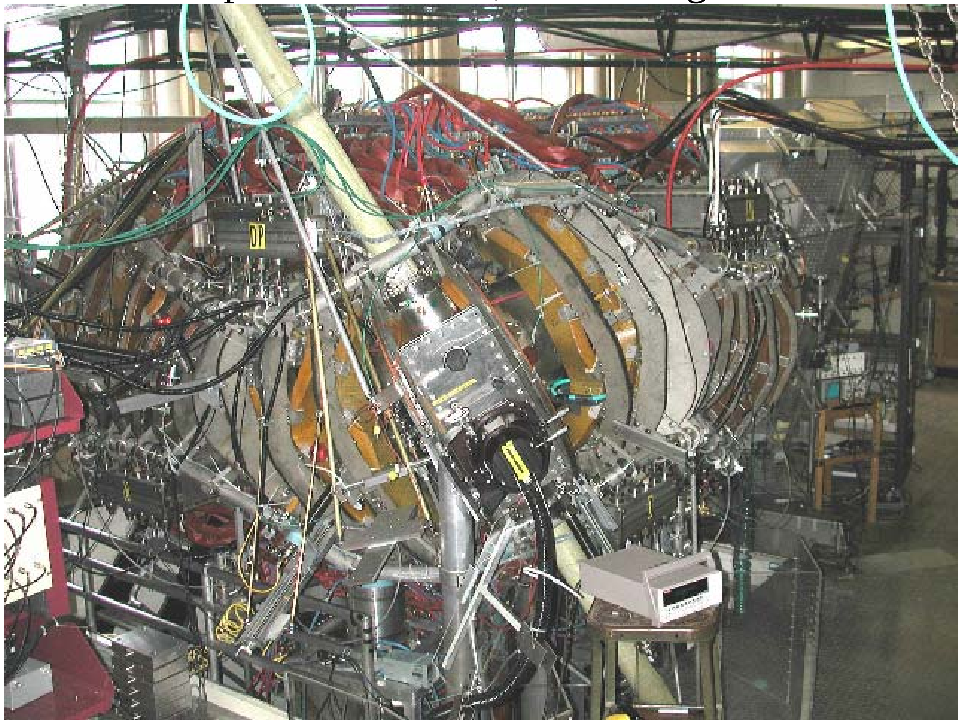
- Best case scenario assumed
  - Present budget is FY 04 funding
  - FY 05: achieve spheromak formation, first comparison to MHD calc.
  - FY 06: achieve 100 kA and/or 100 eV, better MHD agreement achieved
  - FY 07:
    - Build equilibrium and stability control coil sets for 0.1 s pulse
    - Begin design of PoP experiment based on HIT-SI results and calibrated MHD predictions
    - Expected FY07 budget: $970k
      - At + 10% begin 0.1 s experiments
      - At- 10 % drop ½ FTE and a Grad student. May not build coils.

The HSX Program: World's First Experimental Test of Quasi-symmetry

Mission: Explore Improvement of Neoclassical Transport in Stellarators

Quasihelical stellarators have high effective transform, ι_{eff} ~3 (q~1/3)

- Reduced particle drift
- Small neoclassical transport
- Low plasma currents; robust magnetic surfaces



R=1.2m, <a>=0.15m B = 1.0 T
4 periods, ECH 28GHz 200 kW

- **First experimental verification of reduced flow damping with quasi-symmetry**
- **Confirmation of high effective transform and reduction of direct loss orbits**
- **Fast particle effects on MHD modes observed due to improved confinement**
- **Observation of reduced neoclassical thermodiffusion**
- **Experimental verification of 3D neutral code DEGAS**

Near-term Plans

Operation at B =1.0 T

Heating power up to 400 kW

Measurement of core fluctuations and radial electric field

FY07 Plans/Budget

HSX is under-utilized due to funding constraints

FY03/04 Funding Level: $1600/1490K

	FY05	FY06	FY07
2004 Review-Supported Budget Level	$1834K	$1890K	$1949K
Guidance	$1475K	$1519K	$1565K

Key Objectives for FY07

Operation at full design field of 1.0 T ; 400 kW ECH ; Demonstrate electron thermal conductivity difference with quasi-symmetry through power balance and power modulation experiments; radial electric field measurements

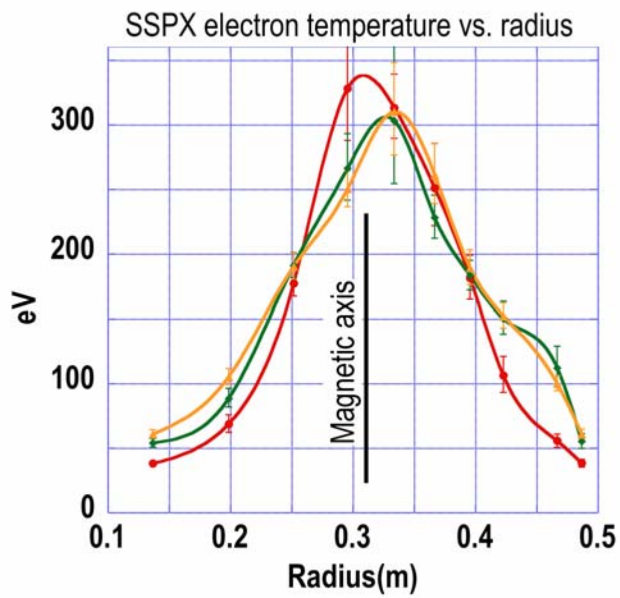
Level Budget at Guidance: **Reduction in staffing of 1 FTE to maintain grad student levels and generate a modest level of needed equipment funds**

10% Decrement from Guidance: **An additional FTE reduction; reduced student/staff interaction and pace of research; no new diagnostic efforts and delay of ICRF inside launch mode conversion heating**

Increment to peer reviewed/supported level: **Maintain optimal program as detailed in successful renewal proposal; maximal contribution to the worldwide and US/PoP Programs from HSX**

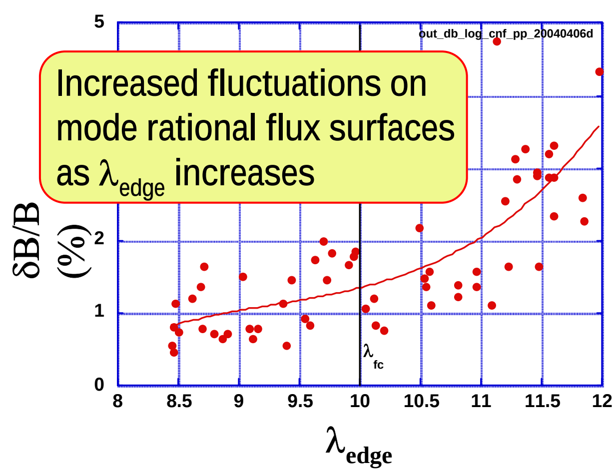
High electron temperatures in SSPX open new regimes for studying energy transport in driven spheromak plasmas

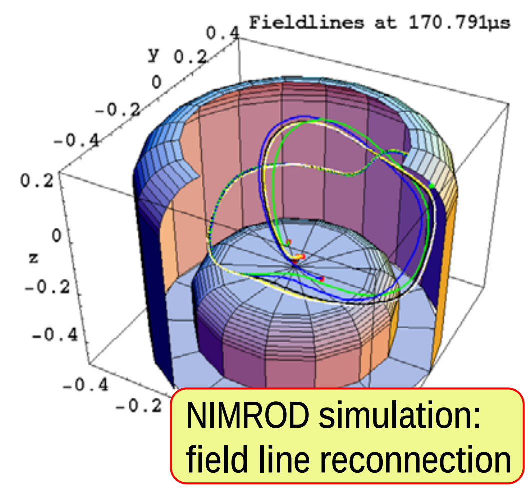
- The SSPX spheromak program addresses two fundamental questions:
  1. What mechanisms are responsible for magnetic field generation with coaxial helicity injection?
  2. What governs the local thermal transport in the presence of fluctuations associated with the helicity transport that maintains the self-organized configuration?



- Te now greater than 300eV. Collisionless plasmas.
- Growing understanding of relationship between internal q-profiles, magnetic fluctuations, and energy transport.
- Improved NIMROD 3d MHD simulations show reconnection during formation and development of closed flux surfaces as discharge evolves.
- New post doc for NSF Frontier Science Center

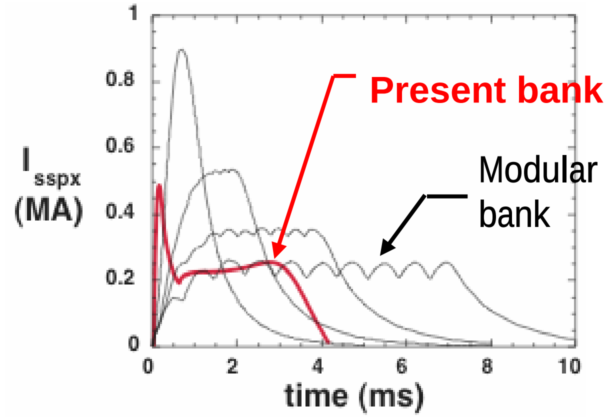
R. Wood, IAEA oral presentation
B. Cohen, APS invited talk



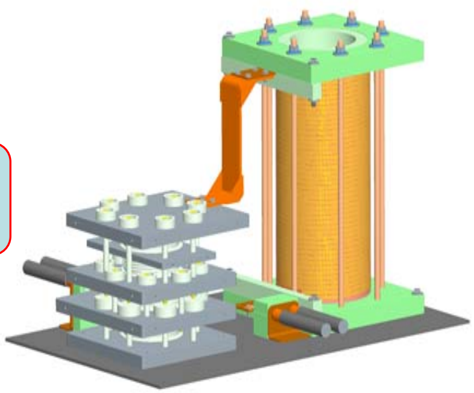


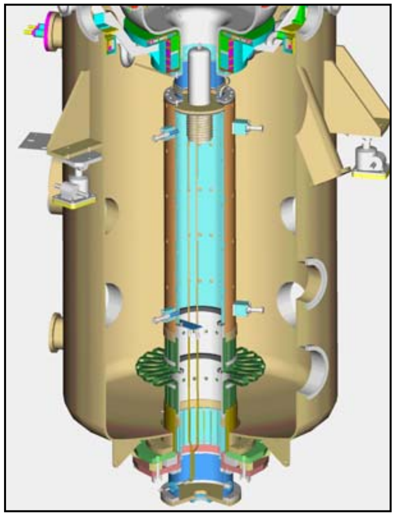
FY06-FY07 budget request supports diagnostic improvements and a full physics program utilizing new solid-state modular bank

- Assumes successful FY2005 ICC renewal competition
- Installing modular bank in FY05 to extend pulse length, increase efficiency, explore multi-pulse buildup. <u>Prototype testing this quarter.</u>
- Guidance: $2.45M will fund experiments with modular bank and provide 2nd Thomson pulse in FY07 for temporal evolution of Te.
- 10% reduction will eliminate Thomson upgrade, and reduce staff.



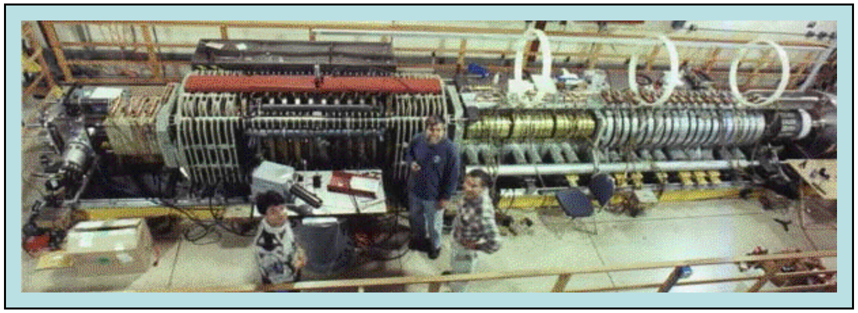
Prototype solid-state module (1 of 30)





Request: $2.7M (10% increase) will allow installation of small diameter injector to test competing models for helicity injection and hiring of post doc to support these experiments.

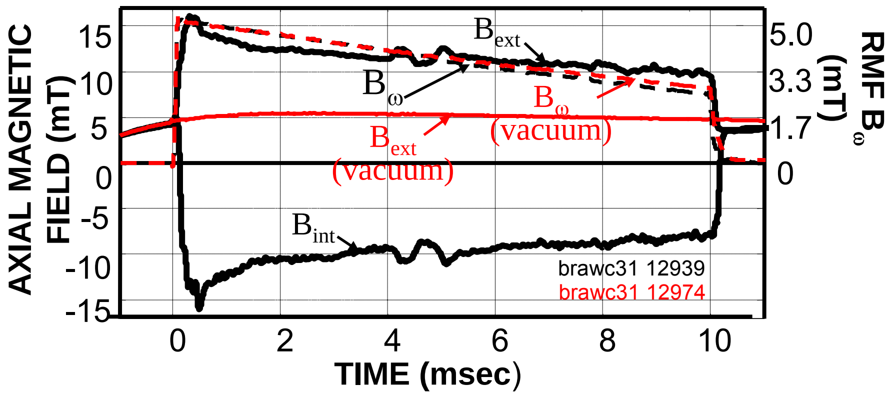
TCS FRC Sustainment Experiment



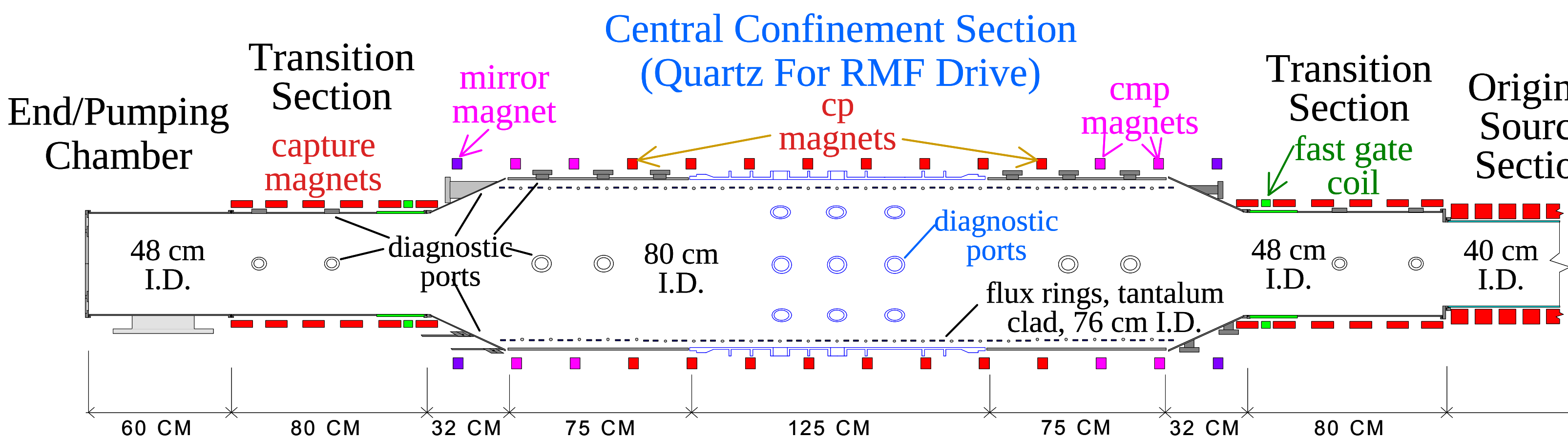
- The overall objective is to produce and sustain hot FRCs using technology that can be extended to large sizes. FRC formation and sustainment using RMF has been demonstrated, in agreement with a comprehensive supporting theory that has been developed.
- Currently building a clean, bakable, UHV chamber as required to form and sustain hot FRCs.
- Additional heating and current drive methods will be developed in the future to produce large s.

Notable Achievements

- Sustained FRCs in quasi-steady state with no sign of destructive instabilities.
- Developed theory & demonstrated strong RMF stabilization of high β plasmas.
- Observed natural relaxation to high β compact toroid in both translated and stationary FRCs with enhanced τ_{conf}.
- Key demonstration of closed field line confinement enhancement using anti-symmetric RMF drive, as previously postulated.
- In last stages of construction of high quality, bakable plasma chamber



FY07 Plans & Budgets for TCS/upgrade

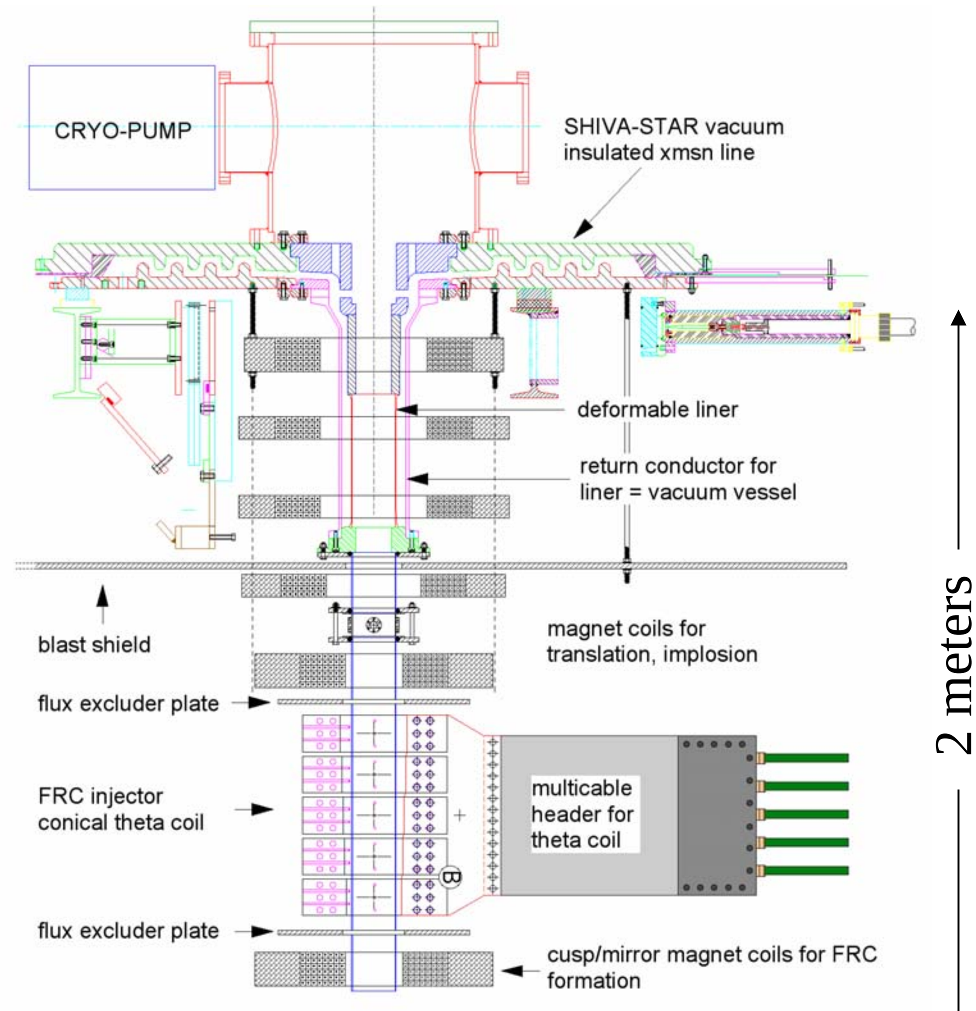


- TCS/upgrade will be run in a clean, high vacuum environment with a baked, discharge cleaned, and wall-conditioned plasma chamber.
- Anti-symmetric RMF current drive will be applied to maximize temperatures and energy confinement times.
- Multi-point Thomson scattering will be employed to measure $T_e(r)$.
- Additional heating and current drive methods will be developed towards production of large s.

- Personnel & lease yearly costs ~ $1,250,000.
- Operational and equipment costs ~ $250,000
- University Overhead ~ $250,000
- Total Cost ~ $1,750,000

Magnetized Target Fusion:
Integrated design
liner on plasma experiment

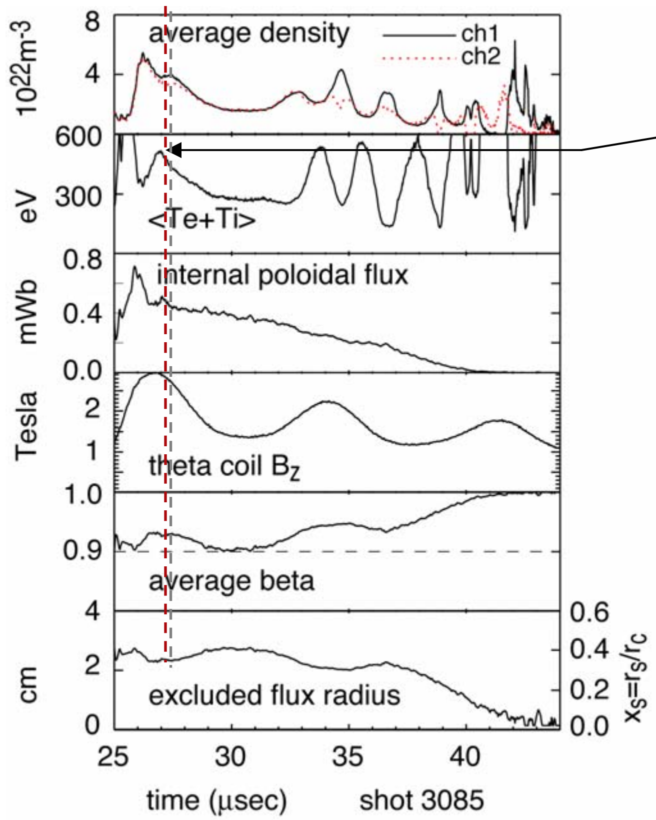
- LANL≈ \$1.4M + AFRL≈\$0.5M
- FRC formation in conical theta coil
- Robust translation v≈12cm/μsec
- compression with tested deformable liner
- Integration of LANL front end with AFRL Shiva-Star implosion bank
- FY 2007 schedule for liner on plasma shots

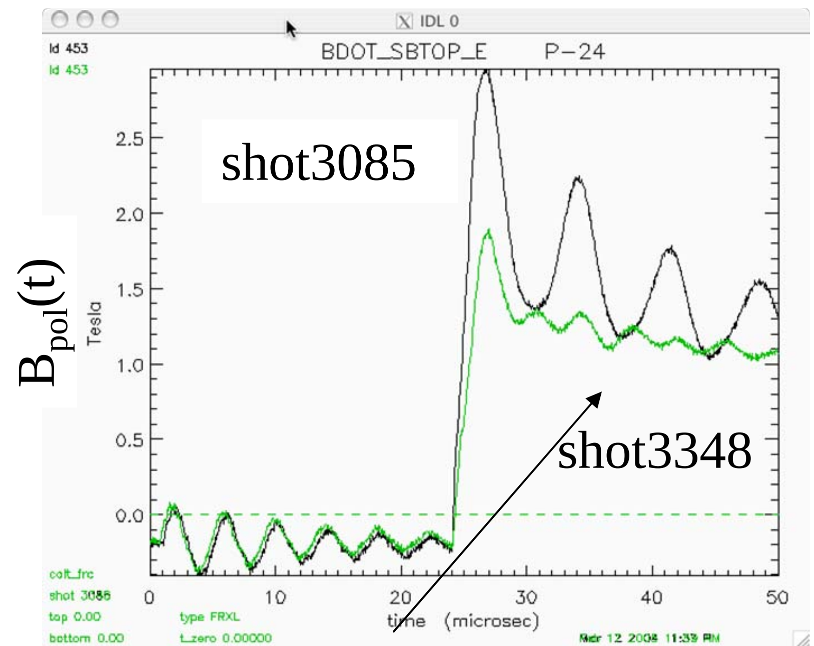


integrated liner on plasma design
- FRC formation with conical theta coil
- translation region
- tapered, deformable 30 cm tall liner, tested 2004, 2005 shots

MTF results: New crowbar switch $\Rightarrow$ should double FRX-L parameters

- Lifetime $\tau_\Phi \approx 10\ \mu$sec
- Density $n \approx 2\times10^{22} m^{-3}$
- temperature $T_e+T_i \approx 250$eV
- Maintain peak n,T $\Rightarrow$double!

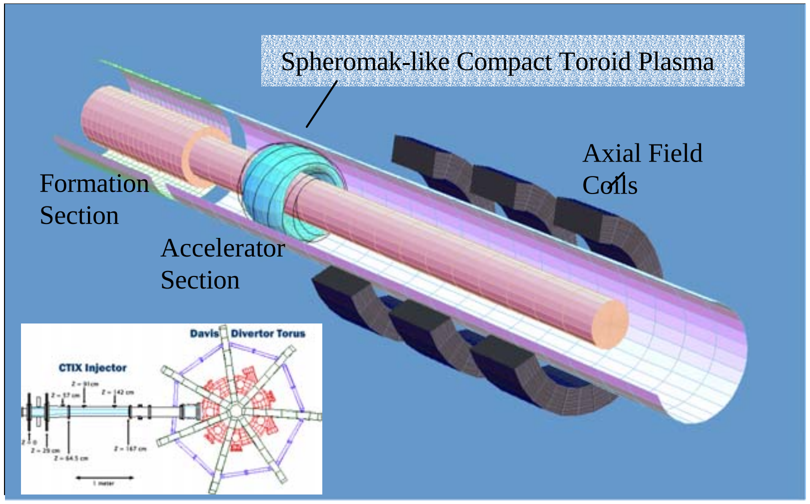




first (non-optimized, 40kV) new CB test vs 70kV shot

Compact Toroid Injection Experiment (CTIX)
UC Davis/Livermore, Livermore CA

- **Program Goals:**
  - Central refueling of magnetically confined plasmas
  - Passive switching for rep-rate SCT accelerator
  - Improve formation and acceleration
  - Increase overall efficiency of the accelerator
  - Increase final SCT density and velocity
- **FY05 Budget: $350K**



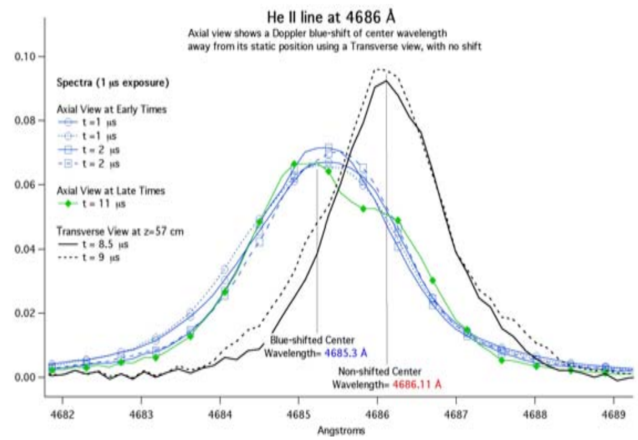
CTIX: Accomplishments and Plans

FY 04-05: Accomplishments

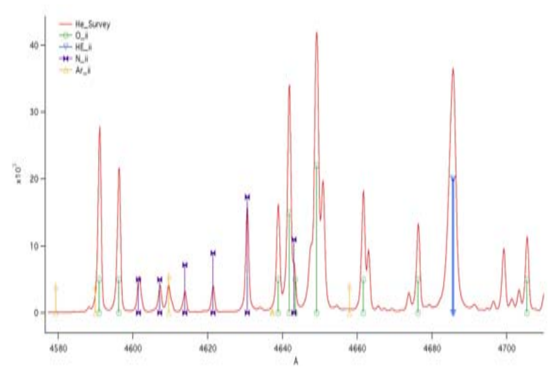
- Impurity identification/ visible spectroscopy
- Ion velocity Doppler measurements
- Fast imaging of SCT rotating while penetrating a target magnetic field
- Fast imaging of density fluctuations
- Quantified radiation profile of moving SCT
- Deflectometry vs. interferometry density measurements
- SCT density increase via accelerator gas injection
- Submitted publication to Review of Scientific Instrument
- Prepared papers for Physics of Plasma

FY 07 Plans

- Impurity mitigation experiment
- High resolution spectroscopy
- Multi-channel deflectometry for density profile measurement
- Design of Halbach array for SCT compression experiment
- MHD SPH Simulation of SCT interaction with target plasma

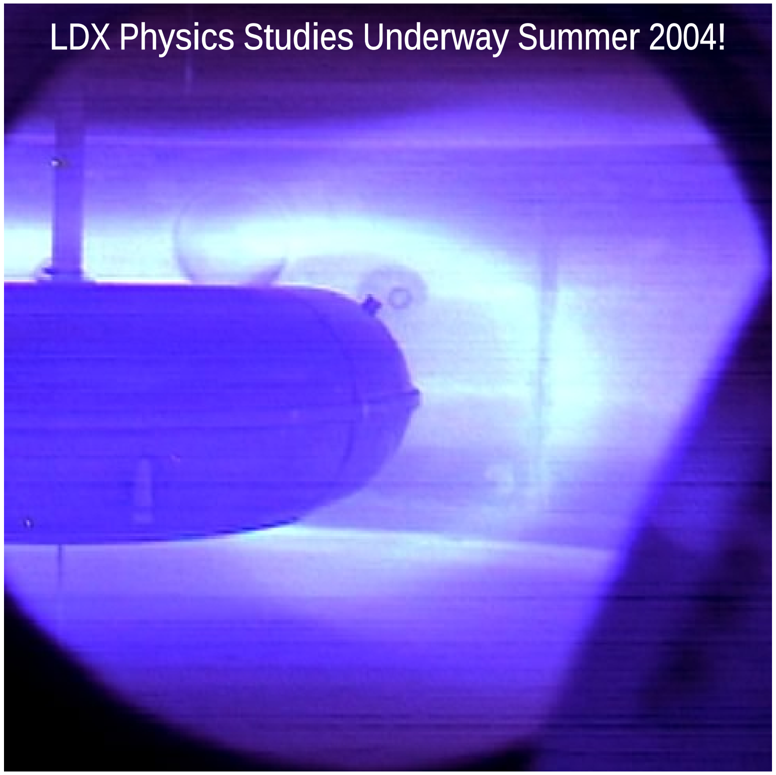


Doppler blue-shift of ion emission is in agreement with expected velocities



Spectral survey has identified all major impurity species

Levitated Dipole Experiment



- Can high-beta ($\beta \sim 1$) plasma be stabilized by dipole compressibility?
- Are high-temperature plasmas well-confined by the dipole field?
- Can adiabatic convection of plasma, confined *without* rotational transform, cause rapid removal of impurities and fusion products?

See *Nuc. Fusion*, 44, 193 (2004): Dipole fusion without tritium-breeding or fast neutron damage.

A partnership of innovative plasma science with magnet technology experts.

Can fusion benefit from nature's way to confine high-beta plasma and advance understanding using the US Fusion Program's only operating experiment with superconducting magnets?

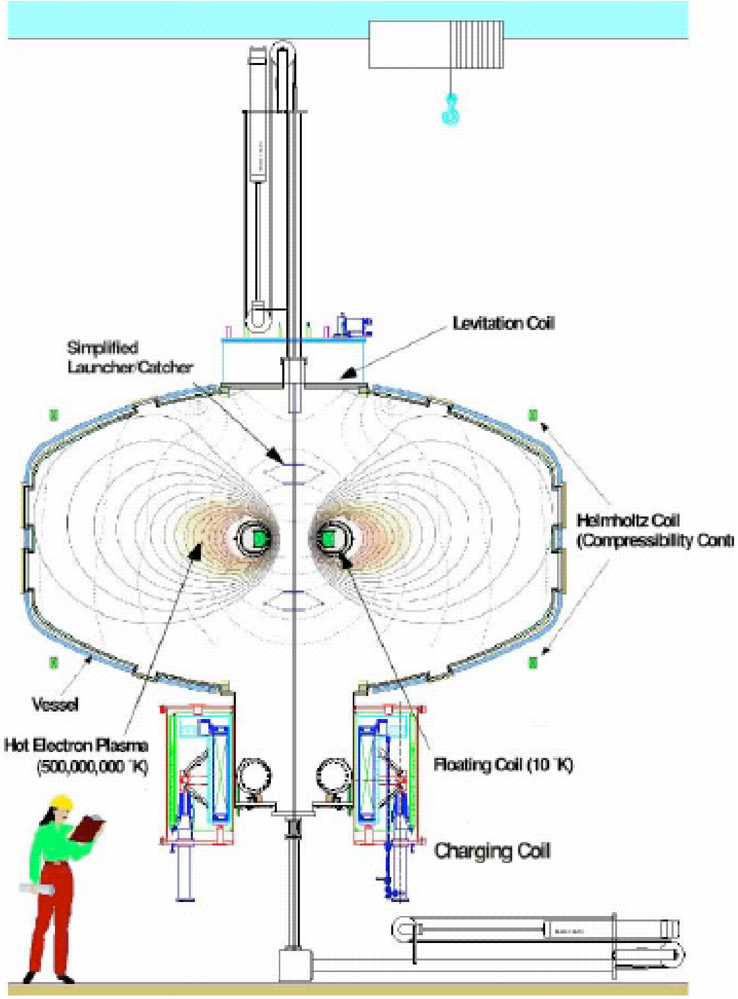
FY04-05 Achievements

- Completed fabrication and integrated testing of high-field superconducting magnets.
- Phase 1: Plasma experiments with supported coil (now).
  - ✓ **Quasi-steady state plasmas** created with more than 10 s multi-frequency ECRH (6 kW).
  - ✓ ECRH creates **central torus of energetic electrons** (10 ~ 30 keV) supported by a cooler plasma extending outward.
  - ✓ Equilibrium reconstruction using arrays of flux loops and magnetic coils show **high beta** (> 7%) with peaked profile and marginal gradients, $\delta(PV^{\gamma}) \sim 0$.
  - ✓ Interferometry and edge probe measurements consistent with **peaked density profile**, beneficial to dipole concept.
  - ✓ **External coils** modify plasma boundary, compressibility.
- Phase 2: Plasma experiments with levitated coil on-track for Summer 2005.

Levitated Dipole Experiment

Space observations, nonlinear numerical simulations, and basic laboratory experiments show high-beta, good confinement, and rapid adiabatic convection of plasma is possible in dipole-confined plasma.

Can we produce well-confined, high-beta plasma with a levitated dipole and understand large-scale adiabatic convection that maintains energy confinement while allowing rapid removal of impurities and fusion products?



FY06 Campaign

- Continue basic physics explorations of high-beta, high-temperature plasma confined by levitated dipole magnet. Use magnetic, optical, x-ray, microwave, and probe diagnostics to study and understand equilibrium and dynamical processes within a high-beta dipole plasma. Edge studies. Investigate effects of convective flows. Continue to develop understanding of dipole particle and energy confinement.
- Install additional ECRH sources and expand operational parameters to higher density and β. Test ability to control pressure profile with high power, multiple-frequency ECRH. Study higher-density thermalized plasmas.

FY07 Campaign ("Full Use Budget")

- Expanded diagnostics for detailed physics observations, and allow increased run time of LDX experimental facility.
- Investigate the unique capability of a dipole for high plasma beta, high energy confinement, and adiabatic convective flows.
- Answer questions to evaluate the potential for attractive dipole fusion with advanced (non D-T) fuels.
- Funding reduction (-10%): would limit purchase of cryogens needed to run superconducting magnets and eliminate support for a graduate student.

Sheared Magnetofluids and Bernoulli confinement

Roger Bengtson, Prashant Valanju, and H. Quevedo
University of Texas at Austin

- Motivation for MBX
  - Create plasma conditions for transitions to Bernoulli states
- MBX program accomplishments
  - Observations made so far
    - Created and observed sonic velocity profile penetration to mirror center
    - Rotation bistability with hysterisis
    - Chiral (reflection) asymmetries
  - Theory developed for MBX
    - Two-fluid theory of rotated plasma bifurcations
  - One M.S. student graduated, one Ph.D. student near completion
- MBX limitations to overcome
  - Need to create higher density plasmas to reduce Alfven speed and decrease neutral fraction

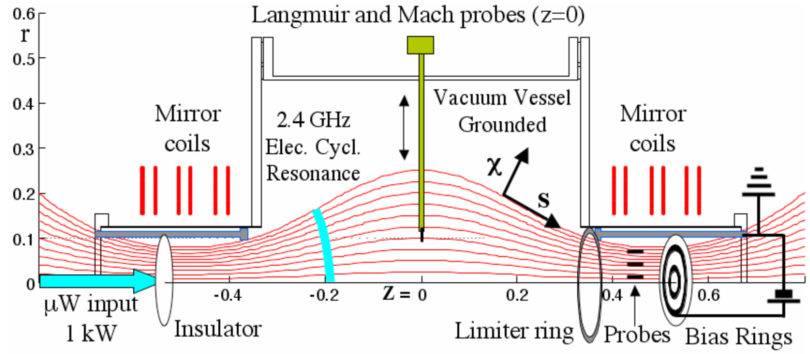


Fig.1 MBX Schematic showing end bias rings.

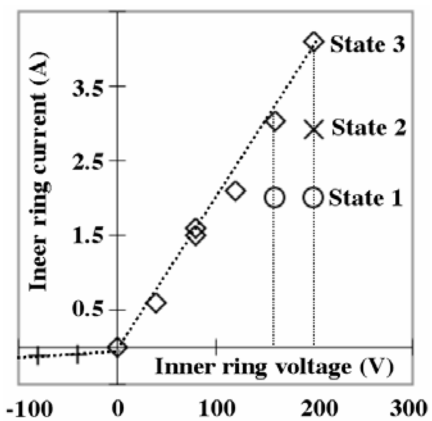


Fig.2 Multiple, stable rotation states (1,2,3) are observed in MBX at high rotation speeds, i.e., at high end ring voltages.

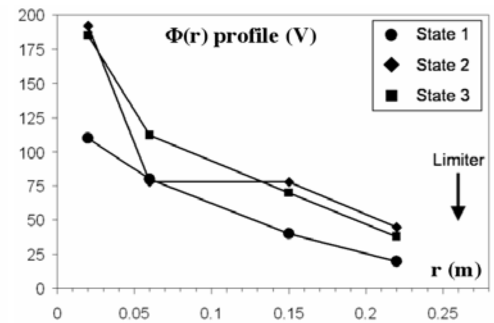


Fig.3 Rotation profiles of the multiple stable states observed with Mach probe in MBX center show spontaneous jumps in radial velocity shear

Sheared Magnetofluids and Bernoulli Confinement
Plans and budget FY 2007

- Motivation
  - Demonstrate and study Magneto-Bernoulli states
    - Are bifurcations due to these?
- Priority tasks (Level funding)
  - Make higher density plasma
    - Higher RF power, and/or
    - Test new plasma sources
  - Make higher rotation speeds
    - Add larger capacitor bank
  - Two-fluid theory of bifurcations
  - Write simulation program
- 10% budget cut
  - Either eliminate PI summer salary or reduce student support.

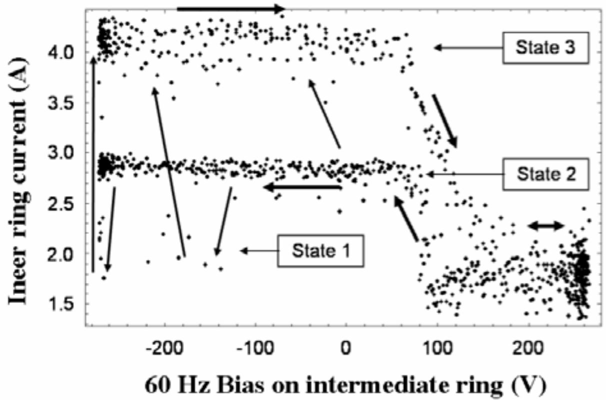


Fig.4 Transitions between stable rotation states in MBX show hysterisis.

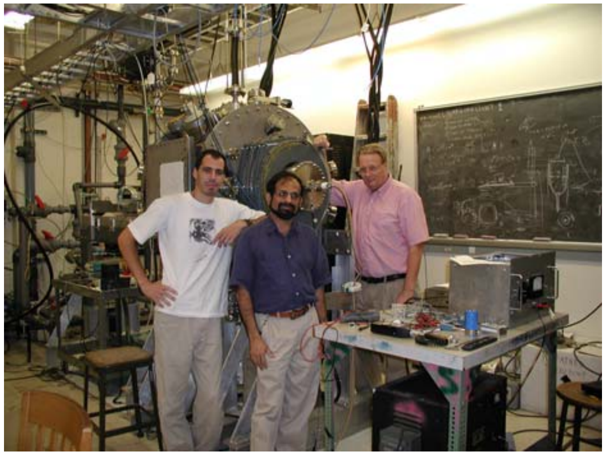


Fig.5 MBX. (H. Quevedo, P. Valanju, and R. Bengtson)

MARYLAND CENTRIFUGAL EXPERIMENT

Mission ***Create a supersonically rotating plasma to augment magnetic confinement by centrifugal force and stabilize MHD interchange modes with velocity shear.***

Achievements(March 2005, FY 2005 budget 480 K$)

- **Supersonic Rotation**: ***ExB*** *rotation to 250 km/s (Mach 3),* T_i *~ 20-40 eV*
- **No destructive MHD modes** : *Stationary to 8ms,* τ_{MOM} *to* $300\mu s$, $\tau_{MHD} \sim 10\mu s$
- **Detached Plasmas :** *HR mode(x2 Mach #,* τ_{MOM} *) – indicates detachment and centrifugal confinement.*
- **Basic Physics :** *First confirmation of MHD dielectric constant; rotation beyond Alfven ionization limit*

FY 06 Goals(budget request 511 K$)

- **HR mode performance :** *use new diagnostics to optimize HR mode; extensively explore parameter space.*
- **Understand MHD stability**: *measure rotation profiles, magnetic modes - correlation with plasma parameters*
- **Assess centrifugal confinement :** *new diagnostics will be implemented*
- **Plasma jet injection** *: experiments on momentum fueling (with HyperV Corp.)*
- **MCX upgrades** : *wall conditioning, higher voltage cap bank, increased midplane B to ~ 1T, mirror B to 2.7 T*

MARYLAND CENTRIFUGAL EXPERIMENT

FY 07 Goals(budget request 532 K$)

New diagnostics, improved understanding, upgraded parameters will allow MCX to assess :

- **Maximum centrifugal confinement :** *measure axial density and pressure confinement for wide parameter space*
- **Possible velocity limit :** *establish nature of any velocity limit for entire range of operation; determine scaling*
- **Relationship of stability to velocity shear :** *complete determination of role of shear in stabilization*
- **Plasma jet injection :** *complete evaluation for fueling of momentum*
- **MCX next step :** *possible POP ?*

Goals and accomplishments of Plasma Science and Innovation Center (PSI-Center)

- Refine present computational tools with sufficient physics, boundary conditions, and geometry to be calibrated with experiments and achieve improved predictive capabilities.
- Areas of refinement of NIMROD and MH4D:
  - Two fluid / Hall physics
  - Kinetic and FLR effects
  - Reconnection, relaxation physics
  - Transport, atomic physics, and radiation
  - Boundary conditions and geometry
- Initial experiments to test and calibrate codes: FRX-L, MBX, SSPX, SSX, HIT-SI, PHD, TCS, ZaP, and Caltech experiments.
- Funding starts March 05

Plans and Budget for PSI-Center in FY07

- Plans for FY07
  - Finish atomic physics package
  - Progress in handling two fluid effects in real time
  - Begin using CAD to interface MH4D to experiments
  - Simulations with anisotropic transport started
  - Complete NIMROD efficiency improvements for EC experiments.
- Budget: $1020k total for UWash, UWisc, and USU.
- At -10% remove ½ FTE, drop one graduate student
- At+10% add two Grad students

Slide from two years ago, … still true

- Results are constrained by diagnostics
- There is insufficient manpower on all the experiments
- Theory and modeling could contribute considerably more*
  *(but a new center is started in FY05!)
- Many experiments take 3 or more years to construct, and many years to complete, because the funding levels do not match the sophistication and complexity necessary for a state-of-the-art fusion experiment
- No experiments even approach the $5M level called for when the ICC program was established
- Tight funding makes it difficult to turn-over the portfolio of projects for new ideas (but competition is stiff, and turn-over is not zero)

Summary

- ICC's are engaged in vibrant scientific research
- ICC's could each benefit from budget enhancements
- ICC's have no wish to be assimilated by ITER
- ICC participants are united to support the American domestic fusion program, including ITER, but….